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Programmable Technologies for Micro- and Nano-Scale Pattern and Material Transfer and Possible Applications for Control of Self-Assembly

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ABSTRACT

Programmable methods for transferring materials to surfaces in patterns can produce structures with micrometer and nanometer scale features. All such technologies involve combinations of information, materials and energy. The materials in additive technologies can originate in the vapor phase, as liquids or suspensions, or as solids. The energy can come from laser, electron or ion beams, or the pressures used in writing, dispensing, jetting or flow methods. Many of the programmable techniques do not require high temperatures, so they can be used to make fine-scale structures of organic and bio-materials, and even live biologicals. Quantitative comparisons of both additive and subtractive programmable methods show that only a few, based on electron or ion beams, or on proximal probes, are capable of making nanometer-scale structures. Assembly methods, notably self- and directed-assembly, should prove to be central to the realization of manufacturable nanotechnology. Programmable deposition technologies may be used to supply materials for, and otherwise control self-assembly processes. The four sets of technologies, namely masked lithography, direct-write techniques, self-assembly and directed-assembly, provide a versatile and powerful toolbox for making micro-and nano-meter scale devices and systems.

INTRODUCTION

Many programmable, data-driven, so-called "direct-write", technologies for producing fine-scale lines on work pieces have been developed in the past decade. The person designing a process flow for the production of some device or system containing micro- or nano-scale features now has many tools at their disposal. These tools are widely applicable for the production of micro-electronics, -magnetics, -optics and -mechanics (MEMS). A recent book provides a convenient summary of direct-write methods and their characteristics [1].

It is worthwhile to compare the direct-write techniques with the conventional methods that have been used with increasing precision for decades to produce integrated circuits. Three types of processes are used by the semiconductor industry, as indicated by the boxes in figure 1. They necessarily involve the transfer of a pattern *onto* the work piece in order to achieve some desired form in a thin layer of material. This is usually done with fixed masks. However, programmable electro-optical or micro-mechanical masks are now being used in some cases, where the best resolution is not required. Two types of material transfer steps are also employed, namely material addition (deposition) or material removal (etching). In the programmable technologies of interest here, the pattern transfer step is accomplished simultaneously with the material transfer process, as shown by the ovals in figure 1.

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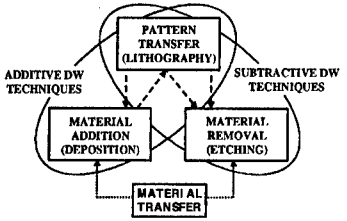

Figure 1. The three processes (boxes) used in conventional lithographic processing, which are employed in pairs (ovals) for direct write (DW) processes.

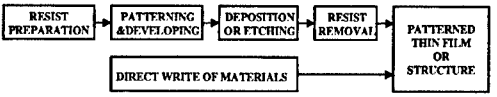

Figure 2. Comparison of the conventional lithographic method of producing patterned thin films (top) with the steps used in data-driven direct-write technologies, which do not involve masks or photoresists.

Another way to appreciate the differences between conventional, masked production of small structures and direct-write techniques is given in figure 2. There it is shown that the conventional approach requires resist preparation and removal steps, in addition to the patterning and material transfer steps. Photoresists require deposition (usually by spinning), baking and development, besides their final removal. The production of complex modern integrated circuits involves the use of over two dozen masks and over 200 process steps.

The programmable technologies, which do not require expensive masks and the use of photoresists, are attractive due to their relative simplicity. Not only do they require substantially fewer process steps, but also their programmability dramatically shortens the time required for the implementation of design changes. Direct-write methods can employ a wide variety of materials and a great diversity of substrates. Often, they are low temperature processes. This expands the variety of materials that can be handled. In particular, it enables the use of organic materials (such as electronic polymers), bio-materials (for example, proteins) and live biological entities (notably viable cells). The low temperatures also make it possible to avoid undesirable processes, such as grain growth. Further, while conventional processing is generally limited to the production of patterned *thin* films, the programmable technologies can produce thick, essentially-3D structures in some cases and fully 3D structures in other instances.

There are limitations to the results that can be obtained with direct-write methods. Inevitably, they are relatively slow because of their serial character. Line widths are limited to sizes greater than one micrometer in most, but, importantly, not all cases. The quality of the patterned materials is less than desired in some cases. For example, if almost fully dense materials are needed, post processing is often required. This adds time to the overall production of a device or system, degrading the advantage gained by the absence of the mask design, production and use steps. In short, programmable processes for pattern and material transfer offer a set of advantages and disadvantages, as is the case with almost all technologies.

This paper provides a survey of some of the salient characteristics of direct-write processes for additive and subtractive production of micro- and nano-scale structures. A review by this author written about a year ago describes the techniques, but does not give a quantitative comparison [2]. Such comparisons for three classes of additive programmable methodologies are given after two introductory sections, one on the three factors involved in all these methods, and a second on characteristics for describing and comparing the technologies. Then, the subtractive techniques are compared. We are concerned both with technologies to make things

in place, which includes conventional approaches and the direct-write methods, and also with techniques in which parts are made separately and then moved into place. Hence, the plethora of assembly processes will be reviewed. The penultimate section deals with the many opportunities to make micro- and nano-structures that are enabled by the relentless development of new materials and new forms of old materials. The conclusion features the techniques that have the ability to produce structures on the nanometer scale. Techniques from each major class of tools (conventional lithography, direct-write and self- or directed-assembly) are likely to be used to make advanced components and systems for both research and commercial production.

BASIC ELEMENTS OF DIRECT-WRITE PROCESSES

There is a triad of requirements for all direct-write techniques. Information dictates the pattern in which the material is put onto the work piece, and energy is needed to effect the transfer of the material. Energy is further required for post processing steps that may possibly be needed. Any of these three factors can limit the rate at which a programmable technique produces the desired structures. The three requirements can be used in a wide variety of sequences, as illustrated in figure 3. It is possible that all three are brought together at once, with ink jetting being an example. Many of the direct-write techniques involve such simultaneous interactions. In laser sintering, a layer of material is put down first and then the pattern and energy are applied in the form of a moving laser beam. In xerography, the pattern is impressed on a drum with electrostatic energy, and then the material (toner) is applied. In self-assembly, the material contains the information for assembly, which is enabled by the application of thermal, vibratory or other forms of energy. Given the many combinations for information and material transfer, the several sources of energy and the wide variety of possible sequences, it is likely that new direct-write methods will be demonstrated in the future.

CHARACTERISTICS OF DIRECT-WRITE PROCESSES

Many characteristics are needed to describe any one direct-write technology, and to compare alternative techniques for a production of a desired device or system. For all methods, additive or subtractive, the source of the information and energy are key considerations. For additive techniques, the source of the material is also critical. For subtractive methods, the disposition of the removed material is sometimes a consideration.

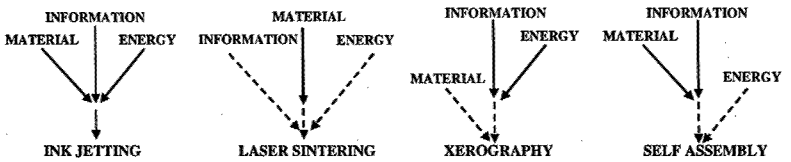

Figure 3. Examples of the ways in which information, material and energy can be transferred to a substrate by direct-write technologies. The solid lines indicate the initial steps and the dashed lines are for subsequent steps in the overall processes.

Several geometrical factors are important. They include the shape, size and orientation of the resolution element, or voxel, employed in a pulsed technique. The minimum and maximum

lateral resolution (line width), and the length and thickness or depth of the voxel are important. The rate of voxel transfer, along with their geometry, size and orientation, determines the linear writing rate for both additive and subtractive methods. The ability to deposit materials on top of each other in multiple passes obviously determines the attainable thickness of the final structure, just as multiple passes in an etching process will determine the depth of a written structure. The precision with which the voxels can be placed on the substrate, or on top of each other, are other significant geometrical (positional) considerations.

Material factors are also central to the description and comparison of additive technologies. Which materials can be transferred, and their state (properties) after transfer, are both critical. The compatibility of particular transferred materials with specific substrates, especially regarding adhesion, is also important for the applicability of a technique. The adhesion of the transferred material to itself can be a consideration. Volumetric rates for vapor deposition methods are critical, as is the range of materials that can be deposited from vapors. Such rates are also important for the many laser-driven methods in which the transferred material starts out in the liquid or solid phase. For writing and dispensing methods, the cross sectional geometries of the fluid stream, both as applied and after relaxation, are of interest. Linear and volumetric rates of writing and dispensing are certainly critical, as are shrinkage, cracking and delamination after deposition. Drop or stream formation, and coherence after impact with the work piece, are significant factors, as is the shape of the transferred material after its deposition. Materials factors are also germane to subtractive processes. For example, particular lasers will etch some materials much more efficiently and cleanly than others.

With so many characteristics of interest for a particular programmable technology, it is clear that a thorough comparison of techniques would be both complex and lengthy. Development and employment of "measures of goodness" or "figures of merit" for comparison of techniques would be challenging. Comparisons of the electrical, magnetic, optical, mechanical and other properties of structures made by the diverse data-driven methods are also complex. In this paper, we will focus on an intermediate level of detail. The source of material and energy will be used to organize the various additive direct-write technologies. This is done in figure 4 for techniques that are described in references [1] and [2]. Then, we will compare three classes of additive methods, outlined by the boxes in that figure, before making a similar comparison for subtractive technologies. We will limit the comparisons to the resolution, thickness or depth of the structures produced and the production rate. Some comments will be made on the variety of materials that can be handled by any class of techniques.

Figure 4 is an imperfect, but useful, way to group the additive technologies. Methods in which the transferred material starts in the vapor phase, and is made in place, have much in common with each other. They constitute a first group, and will be compared in the next section. Techniques in which focused laser beams influence materials that begin as liquids (including suspensions) or as solids (thin films or particles), and are then put in place, make up a second group, which is the subject of the following section. Then, methods in a third group, including various writing, dispensing, jetting and flow methods, are compared in yet another section. It is noted in passing that, for technologies involving focused beams, those beams can be employed for imaging and characterization, as well as the production of fine-scale structures.

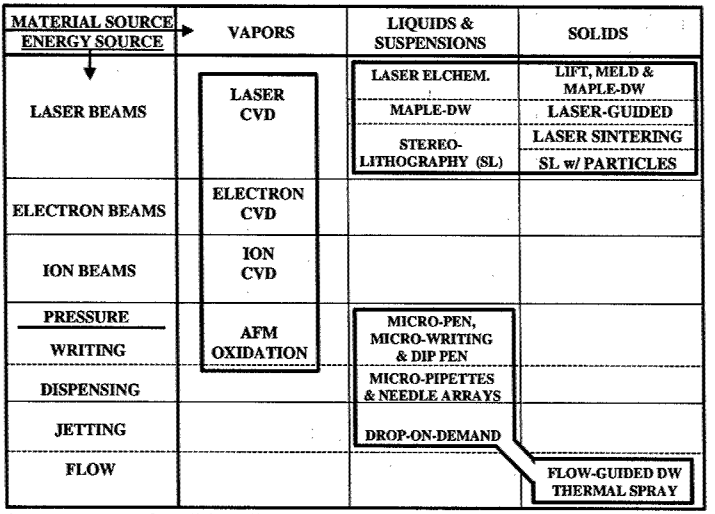

Figure 4. Arrangement of additive direct-write technologies according to the source of the material transferred to a substrate and the source of energy to effect the transfer.

CHEMICAL VAPOR DEPOSITION BY LASER, ELECTRON OR ION BEAMS

The direct writing of materials by the use of focused beams of photons, electrons or ions, or by employing proximal probes, to decompose vapor molecules has two major advantages. A wide variety of materials can be deposited by such means, and truly three-dimensional structures can be made using beams of quanta under computer control. Figure 5 summarizes the characteristics of these processes. It is seen that laser-induced chemical vapor deposition (CVD) offers the ability to make structures over one millimeter in size, but is limited in resolution to about one micrometer. 3D laser deposition from vapors has been demonstrated for refractory materials, such as metallic tungsten and alumina (sapphire). As shown in figure 5, nanometer-scale structures can be made by ion-induced CVD and by oxidation induced on the surface of a silicon wafer by passage of the probe in an Atomic Force Microscope (AFM). However, deposition rates are quite slow. Multiple beams and probes can speed CVD writing.

	RESOLUTION μm	HEIGHT μm	RATE mm/sec	MATERIALS
LASER CVD	~0.1-1	>1000	1	MANY
ELECTRON CVD	0.1	10		MANY
ION CVD	0.01	10	*	MANY
AFM OXIDATION	0.02	~0.001		SiO_2

* 2-30 ATOMS PER INCIDENT GALLIUM ATOM

Figure 5. Major characteristics of beam and proximal probe methods for direct-write CVD of structures. Ovals highlight the ability to produce nanometer-scale features.

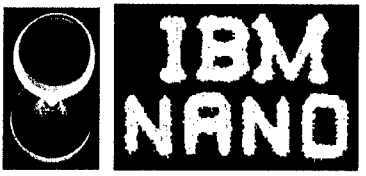

Figure 6. Micro-goblet 2.75 μm in diameter made by ion-induced CVD of carbon [3] and an AFM image of 20 nm wide lines formed by oxidation of Si using a biased AFM [4].

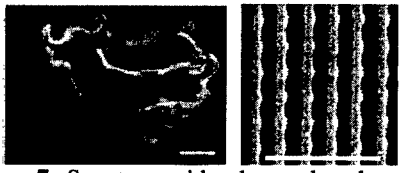

Figure 7. Structures with sub-wavelength features. Plastic bull about the size of a red blood cell formed by two-photon stereo-lithography [5]. Photonic crystal made by use of a femtosecond laser [6]. The bars are 2 μm.

LASER CONTROL OF LIQUIDS AND SOLIDS

Laser control of deposition from vapors was cited in the last section. Lasers are also used for direct writing of materials that begin in the liquid or solid phases, or as suspensions. In general, the several methods in this category are limited to micrometer resolution by diffraction. However, the use of two-photon or very intense femtosecond (fsec) pulses can produce sub-micrometer and sub-wavelength features, as shown in figure 7. Characteristics of laser-guided direct-write processes for materials that start as liquids or solids are given in figure 8.

	RESOLUTION μm	THICKNESS μm	RATE	MATERIALS
LASER TWO-PHOTON	0.12	Few	μm^3/min	POLYMERS
FSEC LASER	0.1	Few		POLYMERS
LASER RAPID PROTOTYPING	~1	~10 μm per layer	Few mm per hour	POLYMERS & OTHERS
LASER FORWARD TRANSFER	1-200	0.1-10	1 m/sec	MANY
LASER GUIDED DIRECT WRITE	2	~1	$10^{-4} mm^3$/sec	MANY
SELECTIVE LASER SINTERING	200	~125		POLYMERS & OTHERS
LASER PRINTING	10	~1	6 cm^2/sec	SEVERAL

Figure 8. Spatial and other characteristics of direct-write processes in which lasers control the deposition of materials from liquids, including suspensions, or from solids.

WRITING, DISPENSING, JETTING AND FLOW PROCESSES

A wide range of direct-write processes involves the mechanical or other transfer of materials onto a work piece in a pattern, often by using pressure or capillarity as the driving force. Their primary features are summarized in Figure 9. Of these, only the dip pen method offers nanometer-scale resolution in the produced patterns. It employs a proximal probe in an AFM to guide the placement of a liquid onto a surface. As is the case for other nanometer-capable methods, the dip pen writing rate is relatively slow.

	RESOLUTION μm	THICKNESS μm	RATE mm/sec	MATERIALS
MICRO-DISPENSING	1-300	< 1-100	>1000	MANY
MICRO-PEN™	50	250	750	MANY
MICRO-WRITING	10	0.005		LIQUIDS
DIP PEN	0.015	0.005	0.001	SEVERAL
NEEDLE ARRAYS	0.1-5 nL	~1	~100 Hz	LIQUIDS
JETTING	40-200	~100	500	MANY
ELECTROCAPILLARITY	Not Used Yet for Direct-Writing			CONDUCTING LIQUIDS
GAS DYNAMIC	1000	8000	5-50 cm/sec	MANY
FLOW-GUIDED	25	Few	0.25mm³/sec	MANY
THERMAL SPRAY	>500	~50	5-50 cm/sec	MANY
PLASMA SPRAY	>500	>5		MANY

Figure 9. Characteristics of processes for patterned writing, dispensing, jetting and flow transfer onto a work piece of materials from liquids, suspensions or other particles.

SUBTRACTIVE PROCESSES

The additive processes noted above are complimented by a collection of direct-write techniques that can etch material from a work piece, as summarized in Figure 10. It is possible that AFM guided etching will produce nanometer-scale lines, as do the ion beam processes.

		RESOLUTION μm	DEPTH μm	RATE	MATERIALS
LASER ABLATION	EXCIM. (248&193 nm)	~1	CAN BE > 1 mm	CAN BE > 100 mm per sec	MANY, ESP. POLYMERS
	Nd (1060 & 533nm)	~1			MANY, ESP. METALS
	CO_2 (10.6 μm)	FEW			MANY, ESP. CERAMICS
LASER PHOTO CHEMICAL ETCHING		FEW	>200	CAN BE >10μm/sec	MANY
ELECTRON BEAM CHEMICAL ETCHING		~1	~mm	10^5 μm³ per sec	SILICON & OTHERS
ION BEAM MILLING		0.05	>10	*	MANY
ION BEAM CHEMICAL ETCHING		0.05	>10	10 X	MANY
MICRO-ABRASION		10	CAN BE > 1 mm		MANY

* 1 μm³/sec/nA Ga BEAM

Figure 10. Characteristics of technologies for programmable removable of materials from substrates.

SELF AND DIRECTED PROGRAMMABLE ASSEMBLY PROCESSES

The hallmark of all functional engineering systems on any scale is their heterogeneity. Homogeneous materials do find many uses based on diverse properties, including electrical (conductors), magnetic (rotors in motors), optical (lenses) and mechanical (strength for structures). However, the devices and systems that characterize the modern world, ranging from integrated circuits to complex electro-mechanical systems, such as video recorders, to communications satellites, all get their abilities by dint of having many different components consisting of diverse materials that are made by numerous different processes.

The abilities to both make components and to assemble them characterized the industrial revolution of the 19th century. Assembly on fine scales, such as watch movements and surgical devices, was greatly advanced in the 20th century. Stepwise fabrication of many devices in parallel, notably for production of integrated circuits, was one of the new and characteristic technologies of the last century. It is widely predicted that self-assembly of nanometer-scale structures will be very important in making leading edge technologies in the 21st century. Such structures will still contain large numbers of atoms, which translates to long fabrication times for slow direct-write methods. Self-assembly may be fast enough to be practical for production of nanostructures in heterogeneous devices and systems, if it can be properly controlled. That is, a combination of self-assembly and direct writing may be commercially viable.

The need for heterogeneity in functional devices and systems seems to clash with the fundamental character of self-assembly, namely its operation independent of external inputs. However, there are three ways in which self-assembly can be controlled. First, if the elements that are assembling are made appropriately, then they will assemble in the desired fashion. Second, the operation of self-assembly requires not only the proper materials, but also the appropriate media and conditions. Finally, limiting the number of elements that can assemble serves to control the size of the resulting structure. Each of these approaches has some advantageous features and some limitations.

Current abilities to produce complex molecules with desired shapes and surface energies enable control of the sub-micrometer and larger structures into which they will self assemble. Whitesides and his colleagues have made geometrical units, with sizes as large as millimeters, which have functionalized surfaces [7]. When put in liquid media and agitated, the units will assemble according to the dictates of the designed surface energies. They term this strategy "programmable" self-assembly, because they control the geometry and surface characteristics in ways that will result in desired structures.

The fact that self-assembly requires the proper conditions, as well as the right material units, can also be used for its control. Here, direct-write technologies might play an important role in controlling what happens on the nanometer-scale. If the pH of the aqueous medium in which self-assembly is occurring is critical to its operation, then jetting or other direct means of delivering acidic or basic solutions could start, speed, slow or stop self-assembly. If the self-assembly process is light sensitive, then the programmable employment of focused laser beams could provide control. In a similar fashion, beams of light could be used to increase the temperature of the medium and hence the rates of self-assembly.

Finally, limiting the number of units available for self-assembly is another means for control of what results. Putting picoliter droplets of dilute suspensions of the units of interest in the correct position at the right time during the production of a device or system might be

possible using jetting technologies. Laser "tweezers" might also be used to control what is put in which location prior to a self-assembly event.

In short, self-assembly must be directed, modulated or other wise controlled to achieve functional components and systems, which are always inhomogeneous. The required control can be exerted in three possible ways: (a) at the unit level by proper design, (b) by control of conditions or (c) by limiting the number of units that can assemble. It can be asserted that all three of these means of controlling self-assembly are "programmable" because each of them can be flexibly sequenced to produce the structure of interest. Which means of control will prove to be useful and robust for specific units and particular target structures remains to be determined from future experiments and simulations.

The inevitable feature of any method involving self-assembly is that the size of the structures within the units will determine the finest achievable structures. Millimeter-sized units with micrometer-scale features will result in assembled components having features only as fine as micrometers. However, there is an aspect of this approach that might lead to finer features. Employment of very thin patterned surface films, which would have both the appropriate overall energies for the self-assembly operation and also in-plane functionality, could yield structures on the nanometer-scale in at least one dimension.

Hopes for production of three-dimensional nano-structures follow from the fact that natural proteins and other complex organic molecules, which have nanometer-scale structures, both self assemble into their characteristic shapes (by complex folding) and then assemble with each other (by aggregation or crystallization). Hence, designer proteins, possibly made by living organisms on the basis of man-made DNA instructions, offer the possibility of making heterogeneous structures on the nanometer scale. DNA has been used to direct the assembly of nanoparticles [8]. Living cells are already being co-opted for the production of drugs and even inorganic materials [9] It seems likely that biological production of designer proteins and other molecular units will be common place in the coming years.

It must be noted that *directed-assembly* of structures into more complex devices and systems, as has been done for most systems over history, is being extended to ever smaller scales. The company Zyvex is developing small-scale versions of pick-and-place machines to make structures of parts with micrometer-scale dimensions, with many assemblers working in parallel [10]. Molecular pick and place devices have been envisioned by Drexler [11]. Proximal probes have been used to move atoms and molecules on surfaces and to cut long organic molecules. Another start-up company, Alien Technologies, is using a fluidic self-assembly approach for putting active electro-optical components into surfaces [12]. Micro-fluidic means of controllably delivering units to a work piece are being developed [13]. They can employ laminar flow to precisely control both the locations on a "growing" assembly at which the new units arrive and their dwell times. Figure 11 is a sketch of a micro-fluidic system for controllable mixing and jetting of nano-particles and -structures from reservoirs onto a work piece. Such a system could also be used for programmed delivery of fluids without suspended particles or parts. Which of these extensions of classic assembly will prove to be commercially viable remains to be determined. It is probably necessary to find some niche uses for each approach in order to sustain the companies developing them while the range of applications for a particular approach is broadened.

The alternative to putting pre-existing parts in place by any means is to grow them in place. Carbon nanotubes were initially made separately, and have been maneuvered into position to form transistors and other devices. Later, it was learned that they could be grown in

specified positions. Growth in place can be viewed as a form of directed-assembly. It is expected that the two approaches to the positioning of nanometer-scale structures will each find wide application.

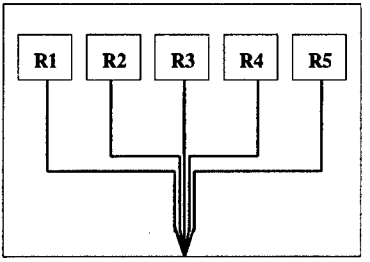

Figure 11. Layout of a micro-fluidic chip for programmable mixing and jetting of fluids from the reservoirs labeled R 1-5. The fluids might be neat or else contain suspended particles or parts for subsequent self-assembly on the surface of a work piece.

Sequential or hierarchical self- and directed- assembly, in combination with lithographically-directed (templated) processes, are likely to be important for the production of complex nano-devices and -systems. It is possible that the major challenge of connecting the micrometer-scale world to nanometer-scale devices will be overcome by using combinations of these many tools.

NEW MATERIALS

The availability of new materials, and new forms of old materials, will have a great impact on the employment of direct-write technologies. This has already been demonstrated by the recent availability of micrometer and nanometer scale particles of materials that can be put onto work pieces in suspensions or by flow methods. Suspensions of quantum dots with remarkable optical properties are now commercially available for use in direct-write processes.

New materials and units will influence assembly processes, as well as processes that do not involve inter-particle forces and self-assembly. Many examples of the production of units could be given. One of them from a recent paper is in figure 12 [14]. It shows particles of silver with regular geometric shapes and closely similar sizes. These were grown by a chemical process, which occurred in the presence of a polymer. Possibly, their surfaces can be functionalized, just as has been done for quantum dots (to avoid agglomeration) and for millimeter-sized units (for self-assembly).

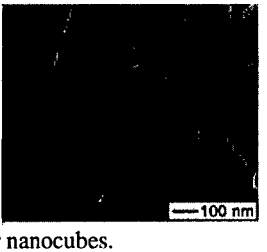

Figure 12. SEM images of silver nanocubes.

It is not clear now whether the capabilities of programmable technologies for making structures will advance more by the development of new processes, by the refinement of existing processes, or by the availability of new or modified materials for use in any of the processes. Probably, important advances will be made in each of these arenas.

CONCLUSION

The collection of programmable, direct-write technologies for production of fine-scale structures is relatively new. However, the methods already show significant practical promise. More important, there are several clear avenues open for their growth in capabilities and applications. Some of them could involve new ways to bring together the information, material and energy that are inevitably required for direct writing of patterns and structures. The employment of new materials and units was just noted. That alone is very significant. So also is the fact that many of the direct-write methods involve only relatively low processing temperatures. This enables structures to be made of organic materials, bio-materials and living cells. It is expected that the production of devices made of organic electronic materials by a combination of direct-write and printing technologies will be significant commercially.

In reviewing the capabilities of the various additive and subtractive direct-write processes, it is seen that only a few operate directly on the nanometer scale in two or more dimensions. Most of the direct-write methods, especially the flow technologies, are not extensible to the nanometer range. It is not surprising that only those beam methods in which the beam can be focused to spots well under a micrometer in diameter qualify for making nano-structures. This generally excludes lasers because of the diffraction limit of light, despite their convenience of operating in air, except for some two-photon and high intensity operations. Electron and ion beams do produce nanometer-scale lines and structures at the expense of working in a vacuum. In general, the technologies that can produce nanometer-scale lines are slow, that is, their linear speeds are low. It is possible to use micro-machining technologies to make systems that have many parallel beams of electrons or ions, so that multiple patterns can be written, or multiple structures produced in parallel.

Proximal probes, especially atomic force microscopes, which intrinsically function on the nanometer scale, are also among the tools for programmable writing with dimensions well under one micrometer. The emergence of devices having many such probes, so that numerous lines can be written in parallel, is an important current development. This will ameliorate the intrinsically slow character of direct-write methods using proximal probes. Examples are given in figure 13 for lithography, dip pen nano writing and data storage.

There is great interest in assembly of units with dimensions on or smaller than the micrometer scale. This is basically due to the requirement that devices and systems have the right materials in the right places to achieve the desired performance. Self-assembly is expected to permit the proper location of large numbers of moieties, with sizes ranging from atoms to millimeter-scale parts. However, it is fundamentally necessary to control self-assembly, if designed and functional structures are to be realized. Happily, there are three basic and broad approaches to the control of self-assembly. Direct-write technologies might be useful for two of the classes of control mechanisms, namely the determination of assembly conditions or the dispensing of limited numbers of units for self-assembly. Meanwhile, new means of classic

"directed" assembly are being developed for fine-scale parts. Hierarchical self- and directed-assembly offer a diverse set of tools for the production of micro- and nano-scale structures.

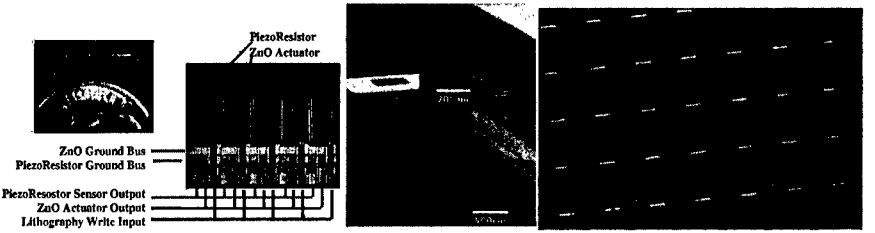

Figure 13. Left: Photograph of 50 piezoelectrically-actuated and piezoresistivally-sensed proximal probes for lithography, and an enlargement of five of them [15]. Center: A 32 probe array (top) and an eight probe array for dip pen lithography [16]. Right: Optical micrograph of some of the 1024 proximal probes in the "Millipede" data storage technology being developed by IBM [17]. An array of 10,000 independently-controlled proximal probe tips was reported recently [18].

In the larger view, there are four classes of methods for producing structures on the micro-and nano-meter scales. They are (a) conventional lithography, with its associated deposition and etching processes, (b) some programmable direct-write techniques, (c) self-assembly methodologies, in which the material units contain instructions for their arrangement, if conditions are proper, and (d) directed or programmed assembly. It seems certain that tools from each of these sets will be used as needed to make increasingly complex and capable devices on the micro- and nano-scales for both research and for commercial purposes.

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